METHOD AND APPARATUS FOR TISSUE TREATMENT AND MODIFICATION

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority from US provisional patent application no. 60/210,531, filed June 8, 2000, entitled, HIGH POWER MICROCHIP LASER BASED ON YB:YAG AS THE GAIN MEDIUM, which is assigned to the assignee of the present patent application and incorporated herein by reference.

FIELD OF THE INVENTION

The present invention is directed to an apparatus and method for obtaining high-peak-power pulses of laser light of extremely short duration through the proper selection of components for a passively Q-switched microlaser with high optical-to-optical, and hence overall efficiency. The improvement in the efficiency allows further miniaturization of the microlaser and reduction of the total cost of the microlaser system.

BACKGROUND OF THE INVENTION

This invention relates to the field of lasers. Many applications require the generation of extremely short, high-peak-power pulses of light from a laser. (For the purpose of this discussion, extremely short will refer to pulse duration of about 1 ns or less; high peak power will refer to peak powers of about 100 kW or greater.)

One of the most effective method for producing short pulses with peak powers in excess of 10 kHz and multi-tens of kHz repetition rate is through microlaser cavity design by utilizing either passive or active Q-switching. (See for Example US patents # 5394413, 5495494, 5844932) Picosecond Q-switched microlasers can produce output pulses as short as large mode-locked lasers, with peak powers as high as commercially available Q switched systems. The entire device can fit into a package of approximately the size of a standard diode-laser package with the possibility of battery-powered operation.

The passively Q-switched microlaser does not require switching electronics, thereby reducing the size and complexity of the total system, and improving the power

efficiency. In addition, there is no need for interferometric control of cavity dimensions, simplifying production of the device and greatly relaxing the tolerances on the temperature control of the device during use. The result is a potentially less expensive, smaller, more robust, and more reliable Q-switched system with very efficient performance. With this combination of attributes, passively Q-switched picosecond microlasers are very attractive for a large range of applications including micro-machining, various bio-medial applications, high-precision ranging, robotic vision, automated production, environmental monitoring, ionization spectroscopy, and nonlinear frequency generation.

SUMMARY OF THE INVENTION

The high and medium power microlaser devices reported by Zayhowski had a pulsewidth in the range of 0.3- 2.2 ns and peak power in the range of 50 – 500 kW. [1] One of the main disadvantages of these devices is their low total electrical to optical efficiency. The low electrical-to-optical efficiency of the high-power microlaser devices based on Nd^{3+}:YAG can be explained by the low optical to optical efficiency, $\eta_{opt\text{-}opt}$, i.e. the efficiency of transferring optical pump radiation (from laser diode pump) to high-peak power output pulse radiation. This efficiency is usually 5-10%. The low $\eta_{opt\text{-}opt}$ is due to the low fractional absorption of the pump. The low fractional absorption for high peak power, short pulse duration microlaser can be explained by low absorption coefficient and short gain medium length. The gain medium length can be increased at the expense of the increased pulse duration. The increased pulse duration forces microlaser to lose its uniqueness and positions them in a row with conventional, commercially available Q-switched systems. The elongation of the length of microlaser resonator cavity from 0.5-1 mm to 5-10 mm results in the increase of pulse duration from 0.1-0.2 ns to 1-2 ns. This in turn causes the microlaser lose its uniqueness, because the pulse duration of few nanoseconds become comparable with that of emitted by conventional Q-switched system.

The low absorption coefficient of the pump is due to the low available consentration of Nd^{3+} ions in the YAG lattice. Higher concentration of Nd^{3+} in the YAG host is impossible due to deterioration of the optical quality of the YAG, making it non-useful laser material.

Laser system.

The apparatus of the invention comprises a gain medium and a saturable absorber disposed within a resonant cavity. The gain medium and saturable absorber are diffusion bonded to undoped pieces of YAG on outer edges. The outer boundaries of the undoped pieces of YAG constitute the resonator cavity. The special coatings are disposed onto these two undoped pieces. Two undoped pieces of YAG with typical thickness of 1 mm each are optional, but added to increase optical damage resistance threshold.

When appropriately pumped, an optical pulse begins to form in the microlaser resonator. During the early stages of the pulse development, the saturable absorber is bleached, increasing the quality, Q, of the resonator and resulting in a short optical pulse. The length of the cavity, the laser gain, the intracavity saturable loss, and the reflectivities of the mirrors are selected such that pulses of less than about 0.3-1 ns duration are efficiently generated with peak powers in excess of 100,000 times the pump power (for example, 200 kW for a 2 W pump).

Although the emission character of MCL is pulsed, it can be pumped and is pumped with continuous wave (CW) laser diode. Microchip laser contains two major components, laser hosts and saturable absorber, positioned at the immediate contact one with respect to another. MCL laser cavity is formed by the outer surfaces of laser host and saturable absorber, or , as in the case of presence of undoped pieces, by the outer surfaces of undoped pieces. Saturable absorber provides Q-switching. This type of Q-switching is called passive, because no external electric or mechanical force is applied. Short pulse length is achieved due to the shortness of the cavity. Typical cavity length is ~ 1-5mm.

Four major output beam parameters of the MCL are:

1. Energy of a single pulse........................E_p
1. Pulse Duration of the individual pulse ...... τ_p
3. Repetition rate of the pulses ....f_{rep}
4. Spatial quality of the beam ....M^2

The first three parameters can be designed following simplified equations, derived from the rate equations of passively Q-switched lasers. The fourth parameter, the beam quality, which can be characterized by M^2 parameter, is the function of the material quality, coating quality, pump quality, thermal load.

The pulse energy can be estimated using the following Equation, [2]

$$E_p = \frac{h\nu_L}{\sigma_L} A_L \Delta R \eta_{out} \tag{1}$$

where $h\nu_L$ is the photon energy, σ_L the emission cross section, A_L the beam areas inside the laser, ΔR the modulation depth of the saturable absorber, and η_{out} the output coupling efficiency (ratio of output coupling and total nonsaturable losses l). The expression for the FWHM pulse width of the Q-switched pulses is,

$$\tau_p = \frac{3.52 \cdot T_R}{\Delta R} \tag{2}$$

with T_R being the cavity round-trip time.

The pulse repetition rate is given by

$$f_{rep} = \frac{g_0 - (l + \Delta R)}{2 \Delta R \tau_L} \approx \frac{g_0}{2 \Delta R \tau_L} \tag{3}$$

where g_0 is the small signal gain, and τ_L the upper-state-level lifetime of the gain medium. The last part of equation 3 is valid far above threshold, where the threshold small signal gain $l + \Delta R$ can be neglected

With typical numbers $\frac{h\nu_L}{\sigma_L}$ =1 J/cm^2 ; $A_L = 5 \times 10^{-4}$ cm^2 ; $\Delta R \approx 0.05$; $h_{out} \approx 0.2$; $L_{res} \approx 1.5$ mm; $g_0 \approx 0.2$; $\tau_L \approx 200$ μ s; we get output laser parameters $E_p \approx 5$ μJ ; $\tau_P \approx$ 1.0 ns; $f_{rep} \approx 10$ kHz, and average power $P_{ave} \approx 50$ mW.

To make higher energy per pulse output we have to choose material with higher saturation fluence $J_{sat} \approx \frac{h\nu_L}{\sigma_L}$, and pump higher area A_L. To reduce pulse duration we need to shorten resonator cavities L_{res}, and to increase saturable absorber modulations ΔR.

The repetition rate is dependent primarily on one internal parameter of the laser, τ_L – upper level lifetime and one external parameter P_{pump}, power of the pump,

$$f_{rep} \propto \frac{P_{pump}}{\tau_L} \tag{4}$$

Using Equations 1-3, one could predict, with ~30% accuracy E_p, τ_p, f_{rep}, of commercially available, OEM-available, and table top models published so far.

The major differences between utilizing Yb^{3+} and Nd^{3+} in microlaser system

The major differences between utilizing Yb^{3+} and Nd^{3+} in YAG laser host is that one can achieve higher absorption of the pump with Yb^{3+} than with Nd^{3+}. This in turn increases the overall efficiency of the microlaser and allows miniaturization and reduction of the cost for the whole microlaser system. In addition the higher absorption coefficient allows the reduction of the whole cavity length and the generation of shorter in temporal duration pulses.

This work proposes to Use Yb:YAG instead of Nd^{3+}: YAG in passively Q-switched microlaser as the laser hosts. The central emission wavelength of the Yb:YAG is different from that of Nd^{3+}:YAG by 3%. This small change allows utilizing the same saturable absorbers in microlasers with Yb:YAG as gain medium as in microlasers with

Nd:YAG as gain medium. Namely the Cr^{4+}:YAG and LiF_2 can be used as passive Q-switchers.

Yb:YAG has many advantages over Nd^{3+}: YAG when utilized in miniature, diode-pumped laser optical devices as the gain medium. Yb: YAG exhibits a complete set of properties favorable for high power diode pumping: [3]

- Very low quantum defect (91% quantum efficiency).
- Very low fractional heating (<11%)
- Very high slope efficiency (77% @ 300K).
- Broad absorption bands (≈ 10 nm @ 940nm).
- High doping level, possible without quenching (>20%).
- No excited state absorption or up-conversion.
- Pump wavelength 940nm, enables the use of very reliable InGaAs diodes.
- High thermal conductivity and tensile strength of the host material.

Properties of Yb: YAG of special interest for high-peak power, shot-pulsed radiation are:

- Long radioactive lifetime of upper laser level (~ 1ms).
- Broad emission bands (generation of pulses as short as 1ps is possible).
- Low emission cross-section (high energy can be stored).

The only severe disadvantage of Yb:YAG is the thermal population of the lower laser level ($612 cm^{-1}$ above the ground level), which leads to the requirements of high pump-power densities (threshold >1.5 kW/cm^2 @ T=300K). This drawback can be circumvented by active cooling design. [4]

Efficient operation of Yb:YAG maybe achieved with pump power near ~10 kW/cm^2). Such values are only available with high-brightness laser diodes.

Comparison of properties of Nd^{3+}: YAG and Yb^{3+}: YAG are summarized in Table I. [5,6]

Table I. Comparison of Laser Properties of Yb:YAG and Nd:YAG		
Material	Yb: YAG	Nd: YAG
τ_{laser}	950 μs	257μs
$\sigma_{pump, abs}$	$7.6x10^{-21}cm^{-1}$	$1.5x10^{-19}cm^{2}$
$I_{pump,sat}$	26.7 kW/cm^2	4.8 kW/cm^2
$\sigma_{laser(emission)}$	$3.3x10^{-20}cm^{2}$	2.6 kW/cm^2
$I_{laser, sat}$	6.1 kW/cm^2	2.6 kW/cm^2
$J_{laser, sat}$	5.8 J/cm^2	0.67 J/cm^2
Quantum Defect	8.6%	24%
Pump Wavelength	942nm	808nm
Lasing Wavelength	1030nm	1064nm
Pump Linewidth	~15 nm	3nm
Lasing Linewidth	~5nm	~0.5nm
Fractional Heating	~11%**	~15%
Pump Diode	InGaAs	AlGaAs

Yb: YAG as lasing material was experimentally demonstrated as MCL low power version [7] as up-scaled CW version in thin disk configuration, [3] and as Q-switched rod configuration as lasing media. [6] In MCL version, 500ps, 1μJ pulses were achieved at 12 kHz. With pump absorbed power ~ 29mW, the emitted average power was 13mW. In thin disk configuration output powers of up to 346 W generated with efficiency electrical-to-optical efficiency 17%. In end-pumped rod configuration up to 340W out was generated. When electro-optical Q-switch was added, 90% of CW power was extracted, at repetition rate of 3-10 kHz. [6] The very lower difference between CW power and Q-switched powers with kiloHertz repetition rate can be attributed to long upper-state level lifetime.

The main point of utilizing Yb^{3+} instead of Nd^{3+} in the YAG matrix is that one can achieve the same laser output parameters out of microlaser system utilizing laser diode pump with factor of five less in output power. To compare output HP (high power) MCL characteristics made of Yb:YAG and Nd:YAG one can use Eq. 1-3.

This is summarized in the two examples below. The first example assumes that gain medium is Nd^{3+}:YAG, the second $Yb^{3=}$:YAG. In both example P_{pump} is the power of the pump, E_p is the output energy of the pulse, τ_p is the pulse duration, w_o is the size of the waist of output beam, P_{peak}, J_{peak}, I_{peak} are the output peak power, peak fluence and peak intensity, f_{rep} is the pulse repetition rate, and $P_{avg, out}$ is the output average power.

Example 1. Microlaser cavity design based on Nd^{3+}:YAG/ Cr^{4+}:YAG.

Undoped YAG	Nd^{3+}:YAG (1-2 wt%)	Cr^{4+}:YAG T_{closed}=40%	Undoped YAG
←---------------------------------Resonator Cavity --→			
1 mm	L_{Nd}=2-3mm	2-6mm	1mm

P_{pump}=10W; E_p=225μJ; τ_p=700ps; w_o= 90 μm; P_{peak}=270 kW; J_{peak}=1.8 Jcm^2; I_{peak}=2.2 GW/cm^2, f_{rep} = 2 kHz, $P_{avg,out} \approx$ 0.4W

Example 2. Microlaser cavity design based on Yb^{3+}:YAG/ Cr^{4+}:YAG.

Undoped YAG	Yb^{3+}:YAG (10-20 wt%)	Cr^{4+}:YAG T_{closed}=40%	Undoped YAG
←---------------------------------Resonator Cavity --→			
1 mm	L_{Yb}=2-3mm	2-6mm	1mm

P_{pump}= 2W; E_p=225μJ; τ_p=700ps; w_o= 90 μm; ; P_{peak}=270 kW; J_{peak}=1.8 J/cm^2; I_{peak}=2.2 GW/cm^2, f_{rep} = 2 kHz, $P_{avg,out} \approx$ 0.4W

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features, and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which reference characters refer to the same parts throughout tile different views.

FIG. 1 is a perspective view of a passively Q-switched picosecond microlaser imbodying the present invention. For illustrative purposes, the microlaser system is separated into pump, the microlaser resonator cavity (microlaser itself), and into output radiation.

FIG. 2 Is the perspective view of the preferred embodiment of the present invention wherein a passively Q switched picosecond microlaser is pumped by the output of an optical fiber, and cavity endfaces are flat or convex. The laser output is frequency multiplied (doubled, tripled, quadrupled, and quintupled) through frequency harmonic generation or divided by virtue of using of optical parametric amplification.

FIG. 3 Is the perspective view of the preferred embodiment of the present invention wherein a passively Q switched picosecond microlaser is pumped directly by a laser diode or laser diode bar disposed in immediate contact with microlaser cavity. The laser output is frequency divided by virtue of utilizing of optical parametric amplification, using periodically poled structure. This embodiment is preferred due to matching to the geometrical configurations of commercially available diode bar and periodically poled crystals, such as $LiNbO_3$ and KTP.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring to FIG. 1, one embodiment of the passively Q-switched picosecond microlaser comprises a short piece of gain medium 5, made of Yb^3+:YAG, bonded through diffusion bonding 6 to a saturable-absorber crystal 7, made of Cr^{4+}:YAG or LiF_2-saturable absorbers. Outer surfaces of both materials, the gain medium 5 and saturable absorber 7 are , in turn, diffusion bonded to undoped YAG pieces 4 and 8 through bonding 12 and 13. All four pieces: 4, 5, 7, 8 are polished flat and parallel on the faces normal to the optical axis 11.

The pump side face 3 of the undoped piece 4 is coated dielectrically to transmit the pump light 2 and to be highly reflecting at the oscillating frequency $_L$. The output face 9 of the undoped YAG piece is coated to be partially reflecting at the oscillating frequency (reflectivity R) and provides the optical output 10 from the device.

The principle behind the operation of the passively Q-switched microlaser is that tile saturable absorber 7 prevents the onset of lasing until the average inversion density within the cavity reaches certain threshold value. After the bleaching of saturable absorber 7, the energy stored in the gain medium 5 is released in one single pulse. After emission of the single pulse, saturable absorber is closed, and accumulation of energy in the gain medium 5 started again due to the continuously present pump 1.

The gain-medium-dependent factors include the maximum inversion density obtainable for the available pump power and the gain bandwidth. The microlaser cavity can be designed to obtain maximum peak power, maximum pulse energy, and minimum pulsewidth.[8] This design can be achieved by varying gain medium active ion consentration (consentration of Yb^{3+} atoms) in gain medium matrix host (YAG), by varying the width of gain medium, width of saturable absorber, and reflectivity of output coupler (R). The width and consentration of gain medium is to be chosen so that to absorb pump effectively. The optical thickness (the thickness along optical axis 11) and consentration of saturable absorber 7 (consentration of Cr^{4+} atoms in YAG host) is to be chosen to provide optimal pulsed operation. The optimal reflectivity of the output coupler, R, in Nd:YAG microlaser , which provide the maximum peak power and shortest pulse duration should be approximately equal to the initial transmission of saturable absorber, $T_{sa,closed}$, R= $T_{sa,closed}$. In the Yb:YAG microlaser the large optical intensities that result from extremely short pulses and high saturation fluence J_{sat} may damage the gain medium 5, saturable absorber 7, interface 6, undoped pieces 4 and 8, or dielectric coatings (mirrors) 3 and 9 much easier than in Nd:YAG microlaser. Due to this, depending on pump conditions, the optimum reflectivity of the output coupler 9 for maximum peak power should be chosen slightly below the initial transmission of the saturable absorber 7,

$$R \leq T_{sa,closed} \tag{5}$$

The typical initial saturable absorber transmission $T_{sa,closed}$ and reflectivity of output coupler can be chosen 50% and 40% respectively, but can be as low as 20% and 20% for intensive pumping.

One preferred embodiment of the application of present invention is shown in FIG. 2. The output of the optical fiber 14 provides sufficient pump intensity 17 for the microlaser to reach (and exceed) threshold, without the need for focusing optics. A frequency-doubling crystal 15, for example KTP ($KTiOPO_4$), is disposed in the path of the laser output beam 10 for generating light 18 at the second harmonic of the oscillating frequency. For example, laser light at an infrared wavelength of 1030 nm, may be converted by the frequency-doubling crystal into green light at 515 nm.

Frequency-doubling crystals may be stacked for generating light at a frequency that is the fourth harmonic of the laser output 10. A second crystal 16, for example BBO (β-BaB_2O_4), is placed adjacent to the first frequency-doubling crystal 15. The laser output 19 is frequency doubled by the first frequency-doubling crystal 15. The output 18 of the first frequency-doubling crystal 15 passes through the second frequency-doubling crystal 16, and is transformed into light 19 at the fourth harmonic of the laser output 10. With this embodiment, diode light 2, transmitted over an optical fiber 14, may be converted by the passively Q-switched picosecond microlaser into laser light 19, which is subsequently quadrupled in frequency by the frequency-doubling crystals 15 and 16 into ultraviolet light 19, which could not be efficiently transmitted using currently available fibers. The, ultraviolet light 19 may be generated several kilometers away from a pump diode 1, at the opposite end of a fiber optic cable 14.

The saturable absorber material 7 and gain medium 5 may both be contained within a common material, as in the case of Yb^{3+}, Cr^{4+}:YAG. In another embodiment, the saturable absorber material 7 and gain medium 5 are two different crystals compromised of dopants in a common host, such as Yb^{3}+:YAG and Cr^{4+}:YAG (where YAG is the common host) and are diffusion-bonded, eliminating the need for an interface dielectric 6.

If a saturable-absorber material 7 is chosen which is non-absorbing of light at the pump frequency, then the placement of the gain medium 5 and saturable-absorber material 7 may be reversed so that the gain medium 5 is disposed adjacent to the output face 9 or undoped piece 8 and the saturable-absorber material is disposed adjacent to the pump-side face 3 or undoped piece 4.

Another preferred embodiment of the microlaser is shown on FIG. 3. The laser diode bar with typical size of the bar of 10 mm is disposed in immediate contact with microlaser cavity. The microlaser cavity is also designed geometrically to be elongated in the direction of diode bar longest side. Each diode in the bar may produce enough radiation to form the separate microlaser cavity. The emission from microlaser can be upscaled in this design in terms of output power. Also this pattern of emission can be conveniently match and effectively coupled into frequency down-converting crystal. The frequency down-conversion can be realized by virtue of optical parametric amplification, by positioning for example, periodically poled $LiNbO_3$ or periodically-poled KTP crystal in immediate contact with respect to output 10 of microlaser. Multiwatt output powers with average pulse repetition rate equal to the pulse repetition rate out of individual microlaser cavity multiplied by the number of lasing cavities can be generated.

The extremely short pulses make the microlaser device attractive for many bio-medical application, including dentistry, delicate skin-treatments, skin resurfacing, cardiovascular revasculation, inner ear surgery and many others. Scientific, aeronautic, space applications may include high-precision optical ranging, robotic vision and automated production.

Additional embodiments include:

23. A passively Q-switched laser comprising:

a) a resonant cavity formed between a first mirror and a second mirror; said second mirror having a reflectivity $R \leq T_{sa,closed}$, and $T_{sa,closed}$ is the initial , unbleached transmission of said saturable absorber to the microlaser radiation light.

b) a gain medium disposed within said resonant cavity for producing laser gain;

c) a pump source for energizing said gain medium; and

d) a saturable absorber disposed within said resonant cavity; said saturable absorber preventing the onset of said pulses until the average inversion density within said resonant cavity reaches a certain threshold value.

24. A passively Q-switched laser for producing high-peak-power pulses of light comprising:

a) a resonant cavity formed between a first mirror and a second mirror;

b) a gain medium disposed within said resonant cavity for producing laser gain;

c) a pump source for energizing said gain medium; and

d) a saturable absorber disposed within said resonant cavity; said saturable absorber, said second mirror, and said laser gain being selected so that output pulses having a duration of less than about 1 nanosecond are generated; said gain medium and said saturable absorber being two separate materials comprised of dopants in a common host; said gain medium and said saturable absorber being bonded by diffusion bonding.

25. A passively Q-switched laser for producing high-peak-power pulses of light comprising:

a) a resonant cavity formed between a first mirror and a second mirror;

b) a gain medium disposed within said resonant cavity for producing laser gain;

c) a laser diode pump source for energizing said gain medium; and

d) a saturable absorber disposed within said resonant cavity; said saturable absorber, said second mirror, and said laser gain being selected so that output pulses having a peak power of greater than about 10,000 times said laser diode pump power are generated; said gain medium and said saturable absorber being two separate materials comprised of dopants in a common host; said gain medium and said saturable absorber being bonded by diffusion bonding.

26. A passively Q-switched laser for producing high-peak-power pulses of light, comprising:

a) a gain medium having opposed first and second faces for producing laser gain from light emitted by a pump source; said first face being highly transmissive to light emitted from said pump and being highly reflective to light at the lasing wavelength; and

b) a saturable absorber having opposed first and second faces; said first face of said saturable absorber being disposed adjacent said second face of said gain medium at an interface; said interface being highly transmissive of light at said lasing wavelength; said second face of said saturable absorber having a reflectivity R, where R is chosen close to initial saturable absorber transmission

27. A method of forming a passively Q-switched laser comprising the steps of:

a) forming a resonant cavity between a first mirror and a second mirror;

b) disposing a gain medium within said resonant cavity for producing laser gain;

c) energizing said gain medium with a pump source; and

d) disposing a saturable absorber within said resonant cavity; selecting said saturable absorber, said second mirror, and said laser gain so that output pulses having a duration of less than about 1 nanosecond are generated

28. The method of claim 27 wherein said second mirror is an output coupler having reflectivity $R \leq T_{sa,closed}$, where $T_{sa,closed}$ is the initial , unbleached transmission of said saturable absorber to the microlaser radiation light.

29. The method of claim 27 further comprising the step of diffusion bonding said gain medium and said saturable absorber wherein said gain medium and said saturable absorber are two separate materials comprised of dopants in a common host.

30. The method of claim 27 wherein said gain medium and said saturable absorber are the same crystal.